Arcing of Electrical Contacts in Telephone Switching Circuits

Part III—Discharge Phenomena on Break of Inductive Circuits

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This is a presentation of a study of the discharge phenomena occurring between contacts on break of an inductive load. The main objectives are: (1) to forward some detailed explanations of the main components of a break transient in terms of basic conduction and emission processes, and (2) to establish the conditions that determine the nature of the transients. The study covered the following: (1) occurrence of interrupted and steady arcs, (2) initiation of reversed arcs in one breakdown, (3) arc initiation under dynamic conditions, (4) initiation and maintenance of glow discharge, and (5) glow-arc transitions.

INTRODUCTION

An important phase in the study of discharge phenomena between contacts is that involving the break of an inductive circuit. A typical switching circuit in its simplest form consists of a battery in series with a coil (electro-magnet), a cable or lead and a pair of contacts. Coils now in use may have inductances of the order of tens of henries and may store as much energy as 10^6 ergs. On break of the circuit an appreciable portion of this energy may be dissipated between the contacts through a steady arc, a series of interrupted arcs, a glow discharge or any of their combinations. In most cases, the energies involved are too high to provide satisfactory contact life from the standpoint of electrical erosion.

The discharge transients obtained are usually complex in nature.[1] A close examination of these transients reveals a great deal of rather curious effects that have not been previously considered in detail. This is a presentation of a recent study of the break transient with the primary objective of furnishing some explanation of the more pertinent phenomena involved in terms of the basic concepts of surface emission and gas conduction.

NOTATION

- a Arc radius or equivalent characteristic length of cross section
- c Local capacitance at the contacts
- e Electron charge
- i_a Current density in the arc
- i_{th} Thermionic emission current density
- i_{ng} Normal glow current density
- i_{ag} Abnormal glow current density
- $(i_{g\text{Limit}})$ Limiting glow current density preceding glow-arc Limit transition
- k Boltzman constant
- l Local inductance at the contacts
- m Mass of contact metal atom
- n Number of consecutive arcs in *one* breakdown
- r Resistance of the local contact circuitry
- s Separation between the contacts
- t Time
- t_{ch} Charging time between breakdowns
- t_{dei} Deionization time following an arc
- t_g Glow duration
- u_s Velocity of contact separation
- u_{ch} Charging velociy defined as s/t_{ch}
- u_{at} Velocity of the metal atoms
- v Arc voltage
- $\bar{v}_n$ Residual voltage at the contacts following a breakdown of n-consecutive arcs
- z Impedance $(l/c)^{1/2}$
- A Constant in the thermionic equation
- A_a Area of arc spot
- C Circuit capacitance
- E Battery voltage
- F Field strength
- I Current
- I_g Current in a glow discharge
- I_m Minimum arcing current
- I_o Initial closed circuit current
- L Circuit inductance
- R Circuit resistance
- T Absolute temperature
- T_b Absolute boiling temperature

T_o	Absolute initial temperature
V	Voltage
V_{ai}	Arc initiation voltage
V_{gi}	Glow initiation voltage
V_g	Voltage drop across the contacts wtih normal glow
α	Thermal diffusivity
φ	Work function
ω	Angular frequency $(lc)^{-1/2}$

GENERAL

A typical circuit consisting of a battery, a coil of an electro-magnet, a cable or lead and a pair of contacts is shown in Fig. 1(a). Due to the usual magnetic core of the coil, this circuit presents some unnecessary complications in making interpretations of the observed contact phenomena. Since our main objective is an understanding of the basic phenomena occurring between the contacts, it appeared justifiable to restrict our work to circuits and circuit elements that lend themselves to simple treatment. Figure 1(b) shows the circuit used in most of this work. All coils used have air cores.

When the contacts are closed, a steady state current $I_o = E/R$ is established in the circuit. At the first physical separation between the contacts, the circuit current will charge the capacitance C causing a voltage rise at the contacts at an initial rate of I_o/C. In the meantime, the separation between the contacts will increase. The first breakdown will occur when the voltage across the contacts first reaches or exceeds the arc initiation voltage corresponding to the separation attained, the atmosphere involved and the *contact surface condition*. Fig. 2 represents diagrammatically the occurrence of the first discharge. abc is the arc initiation voltage versus separation line for a "normal" contact.[2] The

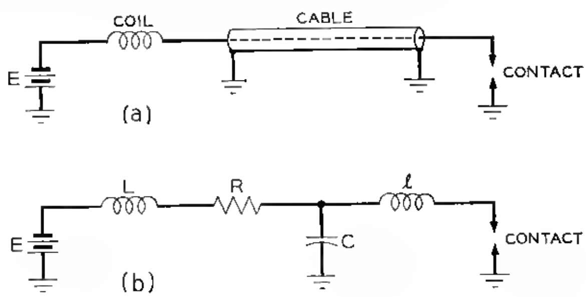

Fig. 1 — (a) Typical relay circuit in practice. (b) Linear circuit used in this study.

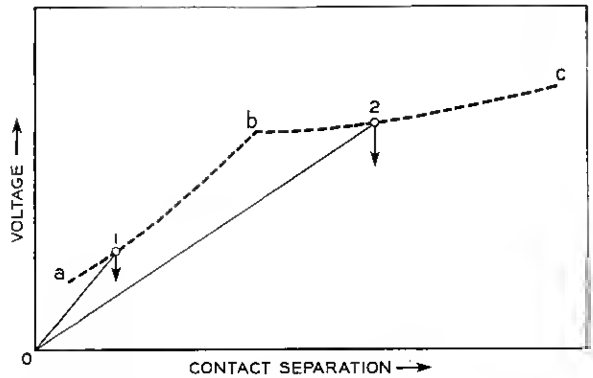

Fig. 2 — Initiation of the first arc between contacts on break of an inductive circuit.

portion bc corresponds to the sparking potentials in the atmosphere. ab corresponds to the range of small separations, of the order of or less than the mean free path of an electron in the atmosphere, where the arc is initiated by field emission through the influence of surface contamintions or films. As was shown in Reference 2, when the cathode surface was carefully cleaned, the constant field line was not obtained and the arc was initiated at the minimum sparking potential of the atmosphere. It occurred on the sides of the contacts along a path much longer than the minimum separation between the contacts.*

Lines 0–1 and 0–2 represent the voltage rise at the contact with small and large shunt capacities. Points 1 and 2 are the respective first discharge points. In the first case, the arc is initiated at a smaller separation and higher field strength without direct influence of the atmosphere. In the second case the arc is initiated at a lower field strength at the spark potential of the atmosphere.†

The first arc established may or may not be maintained depending on conditions that are discussed in the next Section. When an arc is inter-

* With Pd contacts a gross field of 20×10^6 volts/cm was reached between clean contacts without initiating an arc along the shortest gap. According to the Fowler-Nordheim equation a field of about 50×10^6 volts/cm is required to give the necessary initiatory electrons. It is possible, however, that before such a high field is attained a metal bridge is pulled electrostatically[3] to short the gap. The electrostatic stress is roughly given by $0.5 \times 10^{-12} F^2$ Kg/cm^2 where F is the field strength in volts/cm. At $F = 50 \times 10^6$ volts/cm, the stress is 1250 Kg/cm^2 which may exceed the yield stress for the contact metal.

† The first arc may be initiated at an appreciably lower voltage than predicted by the above static consideration. The first break at the contacts usually follows the explosion of molten bridge drawn between the contacts. Thermionic emission can then furnish the initiatory electrons of the arc. This is only possible, however, if the voltage across the contacts exceeds the ionization potential of the metal atoms before excessive cooling of the cathode has occurred.

rupted, it is followed by a recharging process to a new arc initiation voltage when a second arc is initiated. Under certain conditions, the second arc may be initiated at a lower voltage than the first arc due to residual effects of the first arc which may alter the conditions in the gap. This effect is discussed later.

A transient on break with a series of interrupted arcs is shown in Fig. 3. The first arc was initiated at 230 volts and a gross field of 2.5×10^6 volts/cm. All the following arcs were initiated at the spark breakdown potentials in air corresponding to the separations involved. Fig. 4 shows a transient where the arc was sustained with occasional interruptions.

In addition to arcing, one may obtain glow discharge. Fig. 5 shows a transient where glow discharge predominates. Glow initiation and glow-arc transitions are discussed in a later Section.

Fig. 6 shows the methods used for current and voltage measurements. As indicated, direct voltage measurements at the contacts were avoided to eliminate the unnecessary complications of the measuring circuit.

INTERRUPTED ARCS

Conditions for Obtaining Interrupted Arcs

A breakdown from a voltage V_{ai} into an arc corresponds to a rapid voltage drop at the contacts from V_{ai} to the arc voltage v. For most prac-

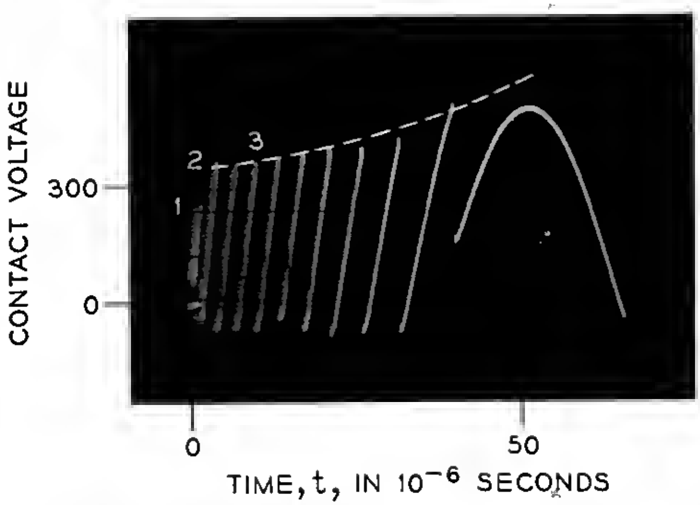

Fig. 3 — Typical contact voltage transient on break of an inductive circuit. Pd contacts in atmospheric air, $E = 50$ volts, $L = 0.2$ henry, $R = 950$ ohms and $C = 510 \times 10^{-12}$ farad. Velocity of contact separation = 40 cms/sec.

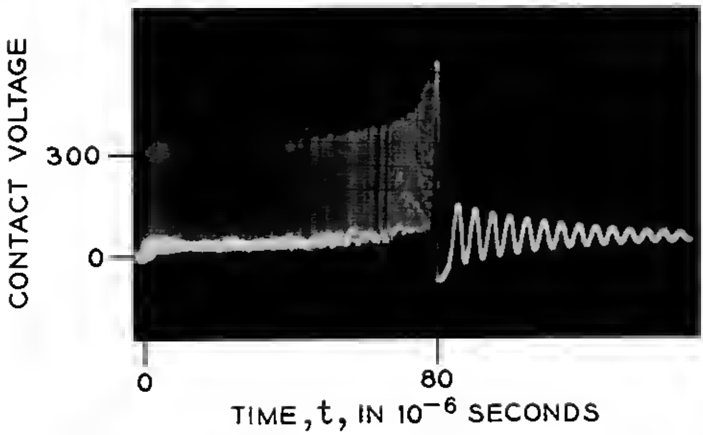

Fig. 4 — Contact voltage transient with sustained arc on break of an inductive circuit. Pd contacts in atmospheric air, $E = 50$ volts, $L = 0.025$ henry, $R = 115$ ohms, $C = 20 \times 10^{-12}$ farad. Velocity of contact separation 40 cms/sec.

tical purposes one may neglect the voltage drop time which is the initiative period of the arc. For the circuit in Fig. 1b, the current through the arc is the summation of the main circuit current and the transient current from the l-c circuit. The transient current is $(V_{ai} - v)(\frac{c}{l})^{1/2} \sin {}^{t}/(lc)^{1/2}$. Fig. 7, (a) and (b), represent diagrammatically the voltage and current transients for lumped and distributed circuits. In both cases the arc is

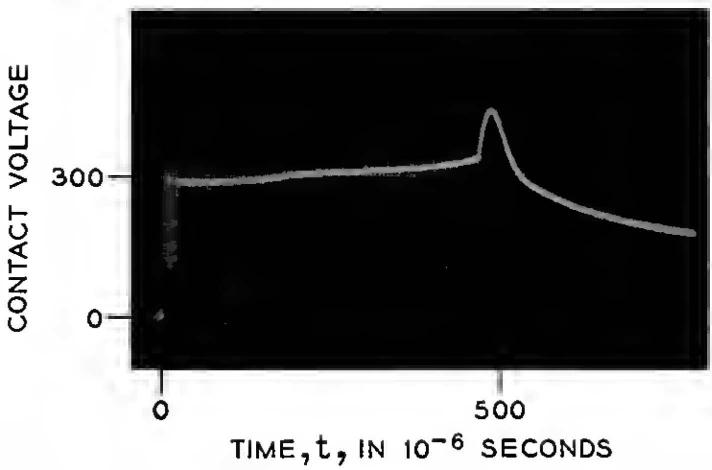

Fig. 5 — Contact voltage transient with glow discharge on break of an inductive circuit. Pd contacts in atmospheric air, $E = 50$ volts, 700 ohms relay coil and $C = 200 \times 100^{-12}$ farad. Velocity of contact separation = 40 cms/sec.

terminated when the current drops to the minimum arcing current I_m. It is evident that the condition for obtaining an interrupted arc is:

$$I_0 - (V_{ai} - v)\left(\frac{c}{l}\right)^{1/2} < I_m \tag{1}$$

It may be pointed out that surface contamination, such as organic activation, tends to decrease both I_m and V_{ai}[2,4]. According to equation 1, one may conclude that contact surface contaminations usually tend to cause a transition from an interrupted arc transient to a steady arc transient. The latter is usually associated with appreciably higher energy dissipation between the contacts and much lower contact life due to erosion.

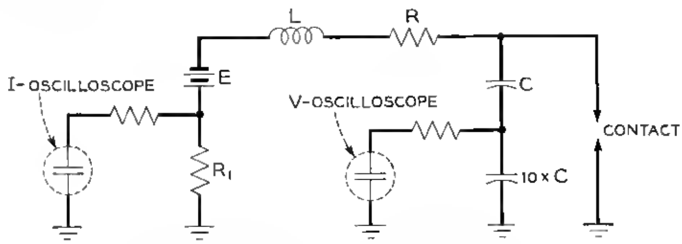

Fig. 6 — Voltage and current measuring circuit.

Residual Voltage Following an Interrupted Arc*

At the interruption of the first arc the voltage at the contact is v, the arc voltage, and the voltage at the capacitor C, Figure 1b, is $\bar{v}_1$ which is usually negative. If the local contact circuit is non-dissipative, the residual voltage is $\bar{v}_1 = 2v - V_{ai}$. For a dissipative circuit with a resistance r corresponding to the frequencies involved:

$$\bar{v}_1 = v - (V_{ai} - v)e^{-(\pi/2)\cdot(r/z)} \tag{2}†$$

for an oscillating circuit, as is usually the case, where $z = (l/C)^{1/2}$. The capacitor C at $\bar{v}_1$ will then recharge the local contact capacity c, $c \ll C$, through the inductance l. If the voltage attained at the contacts is sufficient and the conditions in the gap and at the contact surface are favorable, a reversed arc may be re-initiated, as previously discussed. This process may repeat several times and the residual voltage $\bar{v}_n$ will change sign and decrease progressively. At the end of n arcs, it can be shown that the residual voltage $\bar{v}_n$ is given by:

* The term "recovery" has also been used in the literature.

† Equation 2 and 3 are valid only for small values of r/z. These are approximations of the more general expression given by Germer.[14]

$$(-1)^n \bar{v}_n = v + (V_{ai} - v)e^{-(\pi/2)\cdot(r/z)\cdot n} - 2v \sum_{n=0}^{n=n-1} e^{-(\pi/2)\cdot(r/z)\cdot n} \tag{3}$$

This equation indicates that $\bar{v}_n$ is negative for odd numbers of arcs and positive for even numbers of arcs.* If r/z is neglected, Equation 3 is reduced to

$$(-1)^n \bar{v}_n = V_{ai} - 2vn \tag{3a}$$

For $V_{ai} = 300$ volts and $v = 14$ volts, the residual voltages following the first four arcs are respectively -272, $+244$, -216 and $+188$. These

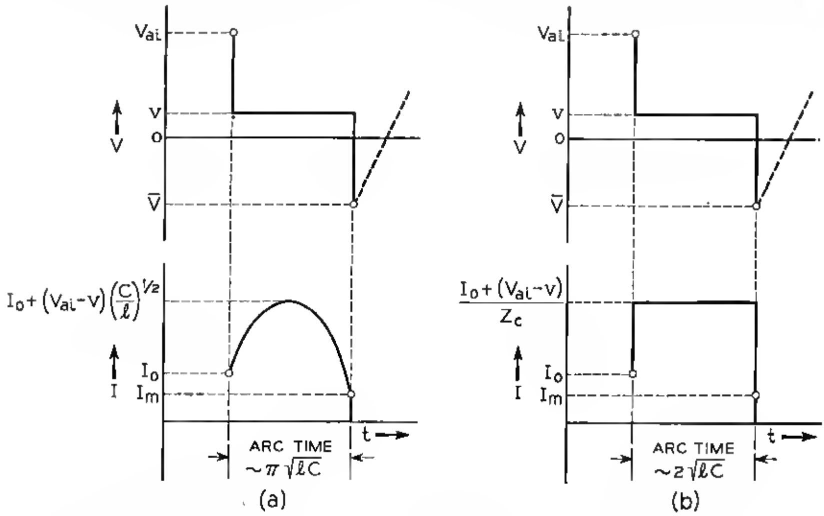

Fig. 7 — Mechanism of interruption of an arc. (a) Lumped circuit elements (b) Distributed elements.

values are numerically higher tban measurements due to neglecting the term r/z. For the circuits used in our experiments r/z ranged between 0.1 and 0.5 and as many as 4 or 5 consecutive arcs have been obtained in one breakdown. Figure 8 shows a transient with both positive and negative residual voltages corresponding to even and odd number of arcs respectively.†

* Except when $\bar{v}_n$ is not too much higher than the arc voltage v.

† The following alternative explanation for the occurrence of high positive residual voltage was considered: the first arc may be extinguished by the formation of a metal bridge due to the arc[2]. This may occur before the capacitor C has attained a negative voltage. This possibility, however, was eliminated. From the measured residual voltages the energies in the arcs were calculated. The heights of the bridges produced were computed (reference 2) and were found to be too small compared with the contact separations.

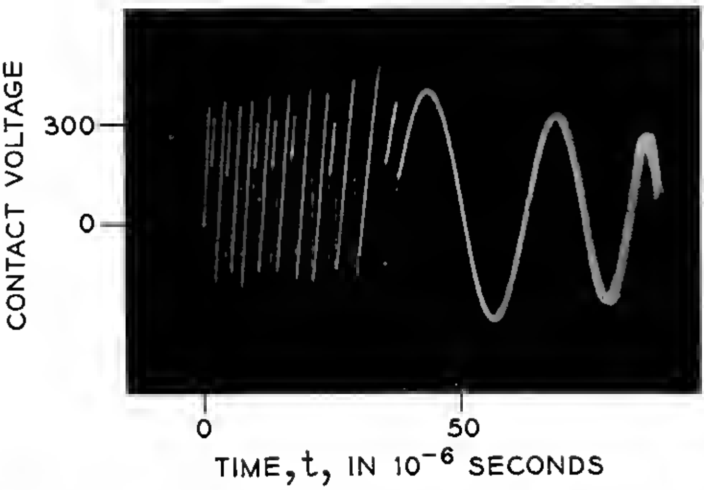

Fig. 8 — Contact voltage transient with interrupted arcs on break of an inductive circuit. Pd contacts in atmospheric air, $E = 50$ volts, $L = 0.010$ henry, $R = 40$ ohms and $C = 900 \times 10^{-12}$ farad. Velocity of contact separation = 40 cms/sec.

Initiation of Reversed Arcs in One Discharge

In one breakdown from a voltage V_{ai} it is commonly observed that a succession of reversed arcs may be obtained. It was shown in equation 3 that the residual condenser voltage $\bar{v}_n$ progressively decreases, numerically, with the number of arcs n. Following the interruption of the first arc, the condenser voltage is $-|\bar{v}_1|$ and the contact voltage is $+v$, the arc voltage. The capacity C will then recharge the local capacitance at the contact through a small lead inductance l. If the circuit resistance is neglected, the maximum voltage the contact will acquire is $-(2|\bar{v}_1| + v)$. If this equals or exceeds the original arc initiation voltage V_{ai}, a second arc is obtained. For illustration, consider a breakdown initiated at $V_{ai} = 300$ volts and $v = 14$ volts. From Equation 3, $\bar{v}_n$ was calculated for the first four arcs at $r/z = 0.0$ and 0.2 The corresponding maximum contact voltages acquired after each arc were also calculated and the results are given in Table I. For $r/z = 0$, column 3, one may obtain, according to this simple circuit consideration, more than 4 arcs, actually 5. For $r/z = 0.2$, which is a reasonable practical value, only 2 arcs may be obtained, column 5, since following the second arc the maximum voltage attained at the contacts is only 256 volts which is less than the initial arc initiation voltage.

It is possible in some cases, however, to obtain a few more arcs than

TABLE I — INITIATION OF REVERSED ARCS BY OVERCHARGING OF CONTACT CAPACITANCE
(Calculated)

$\frac{r}{s} = 0$			$\frac{r}{s} = 0.2$	
(1) Arc No.	(2) $\bar{v}_n$	(3) Max. Cont. Voltage	(4) $\bar{v}_n$	(5) Max. Cont. Voltage
1	−272	−558	−195	−404
2	+244	+502	+121	+256
3	−216	−446	−60	−134
4	+188	+390	+22	+58

V_{ai} = 300 volts, v = 14 volts.

predicted above. These additional arcs have appeared to be initiated at lower voltages than the first arc. This is undoubtedly due to the residual surface and gap effects of the previous arc.* These are discussed in the following section.

Arc Initiation Under Dynamic Conditions — Introduction

In Reference 2 measurements have been presented of the arc initiation voltage between contacts at different separations and surface conditions. These tests are "static" in the sense of allowing enough time to elapse between two arcs to obtain a complete reconditioning of the contact surfaces and gap. With successive arcing, as obtained on break of an inductive circuit or during one breakdown, it was observed that the arc may be initiated at appreciably lower voltages compared with static test results.

One arc may enhance the initiation of a shortly following arc possibly through the effects of: residual ions in the gap or on a cathode surface film, residual metal atoms in the gap and residual thermionic emission. Exactly how each of these effects can enhance the initiation of the arc can be determined only after an understanding of the mechanisms of initiation of the first arc, its maintenance and its termination. It is in order at this point to present a sketchy outline of some plausible mechanisms which are largely of speculative nature. This discussion is also limited to short arcs initiated and maintained with no direct influence of the surrounding atmosphere.

* The additional arcs observed may be partially accounted for by a consideration of the actual value of the arc terminating current which was taken as zero in the above calculations.

a. Arc Initiation

(1) The first initiatory electrons are produced by field emission. The necessary field strength is largely dependent on cathode surface conditions. It is highest for perfectly clean cathode surfaces and appreciably lower in the presence of cathode surface films.[2, 4, 6] This is probahly due to lower work functions or due to the presence of positive ions on a cathode film causing local field intensification.[7] (2) The field emission electrons will travel to the anode where, to qualify for setting the second step in arc initiation, should be able to produce, through evaporation, some anode metal atoms* or possibly atoms of an adsorhed gas or a surface film. (3) The potential drop across the contacts should exceed the ionizing potential of the evaporated atoms to allow ionization by electron collision. (4) Ions produced, on approaching the cathode, will cause local fields high enough to produce electron avalanches. (5) the above processes will rapidly multiply leading to the establishment of an arc.

b. The Established Arc

One main characteristic of the short arc is its very high cathode current density.† This high emission rate indicates that the short arc is not only initiated *but also maintained by field emission.*‡§ Since the total voltage drop across the arc is only of the order of 10 volts, the cathode drop thickness should be very small compared to the total arc length. The cathode drop is followed by the arc column or plasma which is a high conduction medium with equal electron and ion densities, a small potential drop and a relatively high neutral atom density. To maintain the arc: (1) enough metal atoms should be produced to maintain the necessary ionization medium, (2) ions lost by collection at the cathode, hy recombination and by lateral diffusion should be replaced by an

* The arc may also be initiated without the assistance of the anode atoms or ions[8]. The field emission current density at the cathode in this case, was found to reach a critical value before the arc is initiated. It is thought[9] that at this current density the emission spot can attain its melting point through resistive heating. The cathode in this case will furnish the necessary metal atoms for the subsequent steps of arc initiation.

† Recent measurements by the author obtained from arc tracks on Pd contacts produced by short duration *constant* current arcs indicated current densities as high as 50×10^6 amp/cm^2.

‡ Paper by P. Kislink to be published in the Journal of Applied Physics.

§ Recent analytic considerations, to be published by the author, indicate that in such arcs the current density should be dependent on the work function of the cathode material as well as on the product "pressure × separation" in the arc. For instance, for work functions of 2 and 5 volts, our calculations show that the minimum current densities are, respectively, 5×10^5 and 1.4×10^7 amp/cm^2.

equal number of ions obtained by electron-atom collision in the arc column.

c. *Arc Termination*

In general, the arc may be terminated by disturbing one or more of the steady state conditions discussed above. For instance, if the potential across the contacts is decreased to or below the ionization potential of the metal atoms, the necessary ionization process will stop and a deficiency of ions in the arc will result. The negative space charge will immediately upset the arc potential distribution interrupting the high electron emission, etc. The arc is also interrupted when the current drops to the minimum arcing current value. This is a well established experimental characteristic of the arc which has yet to be explained in terms of the more basic concepts. It is thought, however, that a decreasing arc current decreases the pressure and the atom density in the arc column. It is possible that when a limiting current is reached the ionization rate becomes too small to maintain the condition of equal space charges in the arc column. One should expect, accordingly, that providing the contact surfaces* with a film of low evaporation energy should furnish a more adequate supply of atoms to the arc which may then be maintained at lower currents. This is in accordance with observations obtained for active contacts.[4]

Arc Initiation Under Dynamic Conditions; Observations on Break

It appeared of interest to examine the relations between arc initiation voltage and contact separation during the break transient and compare them with measurements made under static coditions.[2] In Fig. 3, the increase in arc initiation voltage with separation is in accordance with the static relation shown as a broken line. During the period 2–3, the breakdowns occurred along longer paths than the minimum contact separation and at the minimum value of the sparking potential. By measurement $t_3 = 20 \times 10^{-6}$ sec, $s_3 = 8 \times 10^{-4}$ cm and $ps = 0.61$ mm Hg $\times$ cm. This is roughly the ps value at the minimum sparking potential in air.[10].

By gradually decreasing the charging times of the transient, by adjusting circuit parameters, it was observed that a point was generally reached when a portion of the breakdowns was initiated at voltages well below the coresponding static initiation voltages. Fig. 9 illustrates this

* The necessary atoms may be obtained from either electrodes or both. Arc transfer observations generally indicate signs of evaporation from both electrodes.

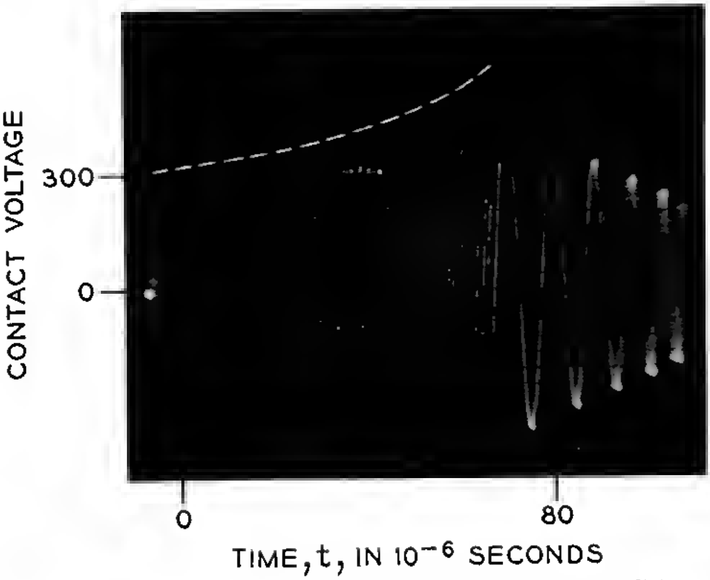

Fig. 9 — Lowering of arc initiation voltage under dynamic conditions. Transient on break of Pd contacts in atmospheric air. E = 50 volts, L = 0.010 henry, R = 40 ohms and C = 270 × 10^{-12} farad. Velocity of contact separation = 40 cms/sec.

effect. In contrast to the static line, shown as a broken line, the breakdown potential shows little change with separation for a major part of the transient. Towards the end, it shows a gradual increase which in this particular case fails to reach the static line. Figure 10(b) is a plot of the ratio $(V_{ai})_{dyn}/(V_{ai})_{stat}$ versus time along the transient.

This phenomenon is attributed to residual effects in the contact gap or on the contact surfaces. In this section, are discussed the possibilities of the presence of residual ions, residuad atoms and residual thermionic emission.

a. Deionization Time

This is determined by calculating the transit time of an ion across the contact gap under the applied field corresponding to the charging of the contact capacitance. For simplification, the initial motion of the ions and the initial field are neglected, the voltage rise is approximated by $V/V_{ai} = t/t_{ch}$ and the field is taken as V/s.

$$t_{deio} = \left(\frac{6m}{e} \cdot \frac{s^2 t_{ch}}{V_{ai}}\right)^{1/3} \tag{4}$$

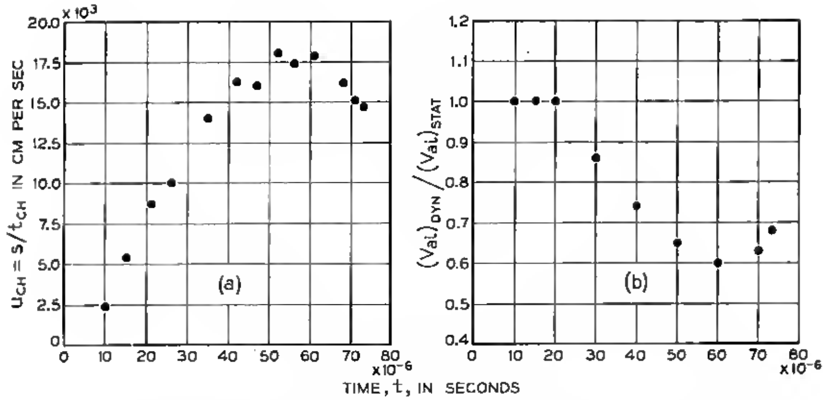

Fig. 10 — Lowering of arc initiation voltage under dynamic conditions.

Defining a charging velocity $s/t_{ch} = u_{ch}$ and a deionization velocity $s/t_{deio} = u_{deio}$ and substituting in equation 4 gives

$$u_{deio} = \left(\frac{eV_{ai}}{6m} \cdot u_{ch}\right)^{1/3} \tag{4a}$$

Following an arc, the contact voltage increases until a new breakdown occurs at V_{ai}. At this instant residual ions from the previous arc could be present in the gap only if $u_{ch} > u_{deio}$, or if

$$u_{ch} > \left(\frac{eV_{ai}}{6m}\right)^{1/2} \qquad (5)^*$$

This is a convenient expression to apply to our measurements, Fig. 9. For any breakdown point on the transient V_{ai} is measured and u_{ch} is calculated from the corresponding circuit current, capacity C and contact separation. For illustration, for Pd contacts and $V_{ai} = 300$ volts, equation 5 shows that for the presence of residual ions, *the charging velocity u_{ch} must be greater than 10^6 cms/sec.* For $I = 0.3$ amp. and $C = 10^9$ farad, $t_{ch} = V_{ai}C/I = 10^{-6}$ sec and for the presence of residual ions the separation between the contacts must be greater than 1.0 cm. This separation is much greater than most separations involved in our field of study. In Fig. 10(b) are plotted the values of u_{ch} during the transient. u_{ch} reaches a maximum of about 1.8×10^4 cms/sec. This maximum occurs because u_{ch} is proportional to sI which is a product of two monotonic functions one increasing and the other decreasing. It is of interest to note that the decrease in u_{ch} caused an increase in the ratio $(V_{ai})_{dyn}/(V_{ai})_{stat}$.

* Deionization by recombination and lateral diffusion were neglected.

From a group of transients similar to Fig. 9, obtained at different conditions, the plot in Fig. 11 was made. It indicates that in general, the ratio $(V_{ai})_{dyn}/(V_{ai})_{stat}$ starts decreasing at about $u_{ch} = 2 \times 10^3$ cms/sec and at 2×10^4 the arc initiation voltage is only 50 per cent of the corresponding static value. As shown in the figure a deionizing velocity of 10^6 cms/sec is just about two orders of magnitude too high to account for this phenomenon. It should be added, however, that while all the ions have cleared the gap, it has been proposed[7] that the life time of an ion on a surface film can be long enough to enhance the initiation of the next arc. If this mechanism is accepted, our data would indicate that the life time of the ions was only of the order of 10^{-7} second.

b. Residual Atoms

After an arc, the contact gap contains some metal atoms evaporated from the electrodes by the arc. These atoms will clear the gap by travelling to and condensing on the electrodes and by lateral diffusion. A crude approximation is given here of the time of recollection of the atoms on the electrodes based on their initial momentum.

One may visualize the arc spot on an electrode to have a temperature distribution extending from submelting temperatures to a range of boiling temperatures, corresponding to the arc pressures. The lowest temperature is probably the normal boiling temperature of the contact metal. At the termination of the arc, the metal atoms produced at the lowest boiling temperature are the slowest and last to recondense on the

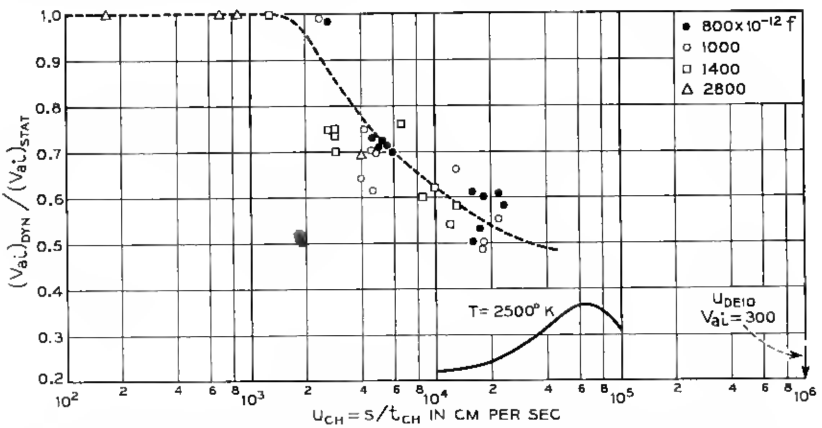

Fig. 11 — Apparent relation between arc initiation voltage and velocity of charging. $E = 50$ volts, $L = 0.010$ henry, $R = 40$ ohms and C as indicated for Pd contacts in atmospheric air.

opposite electrode. An estimate of their velocity may be obtained by assuming thermal equilibrium to have preceded the arc extinction and by using the Maxwellian velocity distribution. The most probable velocity of the metal atoms at the boiling temperature T_b is:

$$u_{at} = \left(\frac{2kT_b}{m}\right)^{1/2} \tag{6}$$

Due to subsequent collisions of the atoms, the velocities thus obtained are probably too high. For Pd at $T_b = 2500°K$, $u_{at} = 6.4 \times 10^4$ cms/sec. In Fig. 11 is plotted a portion of the velocity distribution at the above conditions. It appears that residual atoms can still be present in the gap at the initiation of the next arc. If it is assumed that the presence of Pd atoms in the gap is alone responsible for the lowering of the arc initiation voltage, one may conclude that the sparking potential in Pd vapor is lower than in air. No evidence, however, is available to support this. On the other hand, at least for contacts with gaps short enough to exclude the surrounding atmosphere, or for vacuum contacts in general, it is quite probable that the presence of metal atoms in the gap could enhance arc initiation. This, as pointed out previously, is because the arc cannot be initiated until atoms from the electrode surfaces are evaporated, by electron bombardment or otherwise, to be subsequently ionized.

c. Cooling Time of The Arc Spot, Maintenance of Thermionic Emission

At the interruption of the first arc, the arc spot initially at the boiling temperature of the metal, will start cooling mainly by conduction to the bulk of the surrounding metal. For a certain period, however, it will remain at temperatures high enough to furnish enough thermionically emitted electrons that may enhance the initiation of the following arc. Assuming the arc spot to be a hemisphere of radius "a" initially at a temperature T_b while the rest of the metal is at T_o, the temperature T at the center of the hemisphere is given by [11]:

$$(T - T_0)/(T_b - T_0) = \frac{4}{\pi^{1/2}} \int_0^{a/2(\alpha t)^{1/2}} z^2 e^{-z^2}\, dz \tag{7}$$

Numerically, for $T_b = 2500°K$ and $T_o = 300°K$, T drops to 2400°K and to 1600°K at $a/2\ (\alpha t)^{1/2} = 2.0$ and 1.2, respectively. It is evident that the cooling time is proportional to the area of the arc spot. If the current at which the arc is terminated is I_m and the arc current density is i_a, the area of the arc spot is $A_a = I_m/i_a$ and $a = (I_m/\pi i_a)^{1/2}$. For

$i_a = 10^7$ amp/cm^{27}, and $I_m = 0.5$ amp one gets: $T = 2400°$K at $t = 4 \times 10^{-9}$ sec and $T = 1600°$K at $t = 1.1 \times 10^{-8}$ sec for Pd.

The corresponding thermionic emission is obtained from

$$i_{th} = AT^2e^{-\frac{e\phi}{kT}}$$

with $A = 60$ amp cm^{-2} deg.$^{-2}$ and $\varphi = 4.99$ volts for Pd[12]. At the termination of the arc, $t = o$, $i_{th} = 0.048$ amp/sec^2, at $t = 4 \times 10^{-9}$ sec, $i_{th} = 0.032$ amp/cm^2 and at $t = 1.1 \times 10^{-8}$ sec, $i_{th} = 6 \times 10^{-8}$ amp/cm.^{2} The respective rates of electron emission from the arc spot are 1.5×10^{10}, 1.0×10^{10} and 1.9×10^4 electrons/sec. *This indicates that the initiating electrons may be furnished by thermionic emission if the charging time following the first arc is of the order of or less than about 5×10^{-9} sec.* This time is more than an order of magnitude too small compared to the charging times involved in the data of this section. One may, therefore, exclude the thermionic emission as an explanation for the low arc initiation voltages obtained.

The initiation of reversed arcs, however, may be enhanced by thermionic emission from the previous arc spots since the recharging times involved, $\pi(lc)^{1/2}$, are usually very small. l and c are usually of the orders of 10^{-7} henry and 10^{-11} farad and the charging time is of the order 10^{-9} sec.

ESTABLISHMENT OF GLOW DISCHARGE AND TRANSITION INTO AN ARC

For the circuit in Fig. 1(b), it was observed that on break of the contact, glow discharge was observed under certain circuit and contact surface conditions. An obvious requirement was that the voltage across the contacts should exceed the glow discharge voltage of the contact in the surrounding atmosphere. This requirement alone, however, was not sufficient as in some cases no glow could be detected, in others glow was established and maintained and in other instances glow was followed by a transition into an arc. In this section is presented an experimental study of the conditions that determine the nature of the discharge.

Cathode Current Density in Static Normal Glow

First, measurements were made of the cathode current density in a static normal glow. This was done for palladium and gold contacts in dry atmospheric air at 25°C. In each case the cathode was the flat end of a cylinder and the anode was a larger parallel flat surface of the same material as the cathode. The circuit in Fig. 12 was used. The contacts were

cleaned by filing then washing with methyl alcohol and distilled water. The contacts were slowly brought together until glow discharge was established. Before measurements were made the circuit current was increased to allow the glow to cover the entire cathode flat surface as well as a portion of its cylindrical surface. By allowing the contacts to glow for about 20 minutes, the occasional arcing first observed was eliminated and a steady glow was established. The cathode was observed under a microscope and the current was adjusted to obtain a glow just covering the flat cathode area. From the measured current and the cathode area, the cathode current density was determined. The results are given in Table II.

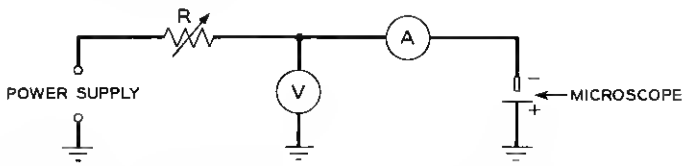

Fig. 12 — Circuit for measurement of cathode current density in normal glow discharge at static conditions.

Observations on Glow Maintenance and Glow-arc Transitions

The simplified circuit in Fig. 13 was used. The contact cathode was the flat end of a cylinder. The cylindrical portion was tightly fitted into a block of an insulating material allowing an exposure of the flat end and a cylindrical area less than 10 per cent of the flat area. The anode was a parallel plain surface of the same material.

To avoid the unnecessary complications of a measuring circuit connected to the contacts, the plates of a cathode ray oscilloscope were, instead, connected across a capacitor, 10 times C, in series with the circuit capacitor C. From the transients obtained, it was possible to identify glow discharge, steady arcs and interrupted arcs. Four typical transients are shown in Fig. 14. Transient A shows a case where glow discharge was established and maintained for the entire half period of the circuit. In transient B glow was not detected and, instead, interrupted arcs occupied the entire half period. In transient C, glow discharge was maintained for a short duration 1–2 followed by interrupted arcing, 2–3. At point 3 the circuit current was high enough to maintain an arc and a steady arc was obtained, 3–4. Transient D is similar to B where glow discharge was undetectable. The multiple discharge in D, however, lead to the steady arc 2–3.

Before presenting our measurements and discussion, a review is given

TABLE II — CATHODE CURRENT DENSITY IN STEADY NORMAL GLOW IN DRY ATMOSPHERIC AIR AT 25°C

Electrodes	Cathode Diameter, cm.	Glow Current, amp.	Cathode Current Density, amp./cm²
Pd	0.05	0.010	5.1
	0.10	0.033	4.2
Au	0.05	0.017	8.6
Ag*	—	—	9

* Measurement by F. E. Haworth.[13]

here of the process of the initiation of the steady arc which was explained in detail in reference.[5] For the inductive circuit in Fig. 13, when the proper contact separation is reached, a first breakdown will occur discharging the local capacitance at the contacts. This is followed by recharging from C through L and a second breakdown. This will repeat while the circuit current will increase in a discontinuous fashion. If it reaches the minimum arcing current of the contact, a steady arc is established, otherwise, the transient will be made up entirely of local multiple discharges. Figures 14D and B are the main condenser voltage transients corresponding to the above two cases respectively.

The interrupted arcs, or multiple discharges, and the steady arc constitute the two processes of conduction that are commonly obtained when the voltages involved are below the spark breakdown potential of the surrounding atmosphere. In such cases, the arc initiation is dependent on the contact material and its surface condition and is independent of the atmosphere.[2] If the voltages involved are equal to or greater than the minimum sparking potential of the atmosphere, the initiation of a breakdown is primarily dependent on the atmosphere. This breakdown, however, may in addition lead to a glow discharge as discussed above. This immediately raises the question as to whether breakdowns leading to an arc and breakdowns leading to a glow discharge are initiated at the same potentials. For this purpose the following experiment was performed.

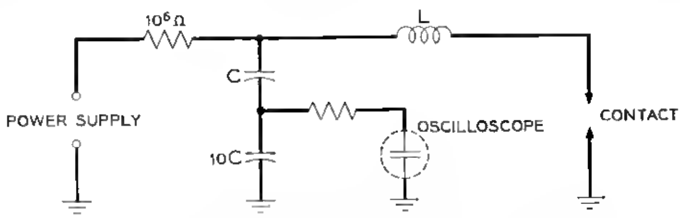

Fig. 13 — Simplified circuit for the study of glow-arc transitions.

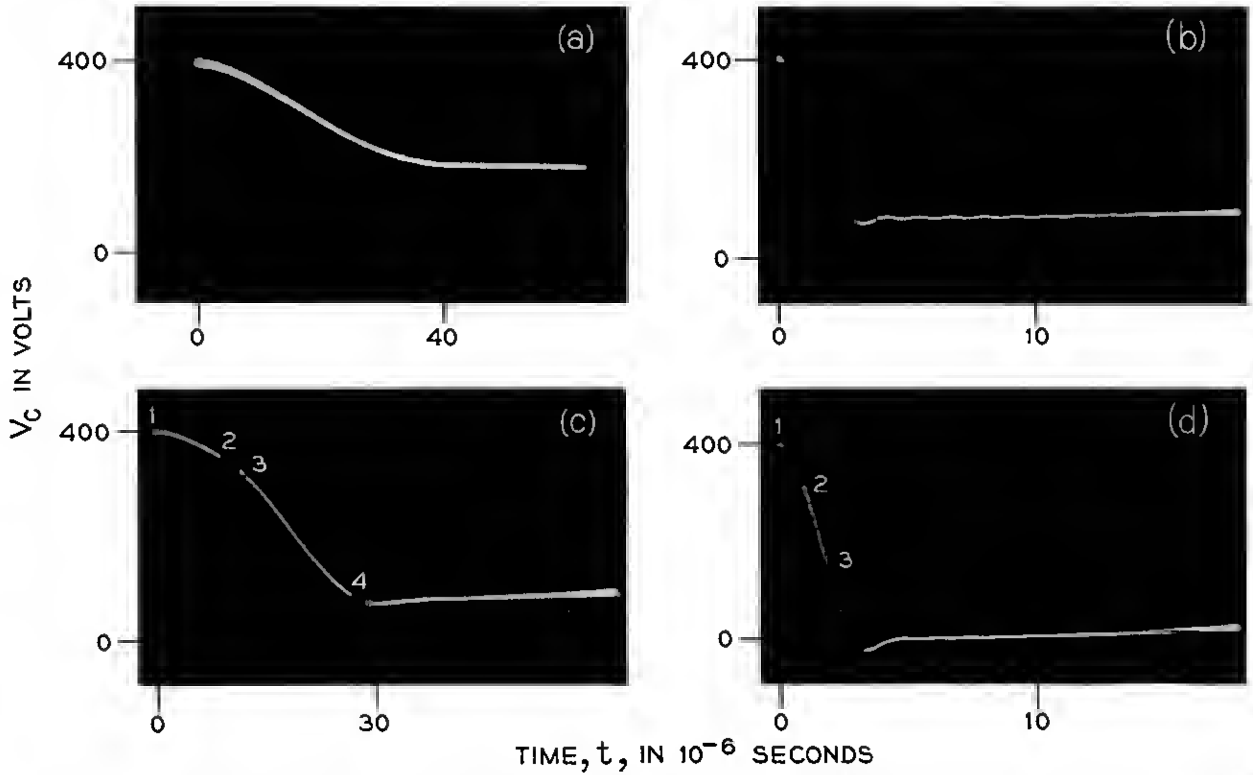

Fig. 14 — Voltage transients at circuit condenser. A: all glow. B: no glow, only a series of interrupted arcs. C: glow-interrupted arcs — steady arc. D: no glow, interrupted arcs — steady arc — interrupted arcs.

Initiation Voltage of Glow Discharge

The cantilever bar setup previously used for similar measurements of arc initiation voltage as function of separation[2] was used here. By varying the separation the corresponding glow initiation voltage was measured. For each separation a measurement was also made of the *arc* initiation voltage. The results are given in Table III. The results indicate that both arc and glow are initiated at the same voltage for the same separation. One may, therefore, conclude that *at least the first few steps involved in the process of the breakdown are the same whether they lead to a glow discharge or to an arc.* In many cases, it was observed that the arc was preceded by a period of glow discharge. This was not found, however, to be the general case as discussed in the following section.

TABLE III — GLOW AND ARC INITIATION VOLTAGES AS FUNCTIONS OF CONTACT SEPARATION FOR PD CONTACTS IN DRY ATMOSPHERIC AIR AT 25°C.

S: 10^{-4} cm.	1.5	3.0	4.5	6.0	7.5	9.0	10.5	12.0	13.5	15.0	16.5	18.0	19.5
V_{gi} : volts	320	320	340	380	400	420	450	480	500	520	540	560	590
V_{ai} : volts	310	320	340	370	400	420	450	470	490	510	540	570	590

Glow-arc Transition

The experimental setup used is shown in Fig. 13. By systematic variation of the circuit parameters *Vo, L and C*, a variety of transients was obtained and recorded. Samples of typical cases are shown in Fig. 14. For transient stability and reproducibility, it was found necessary to exercise extreme care in securing good contact surface cleanliness and in maintaining it during the experiment. The presence of organic vapors, humidity, films of grease or oil, fingerprints, etc., usually led to erratic results. *The general effect was an inclination towards more arcing and less glow discharge.* Only by proper cleaning of tbe contact surfaces and allowing the contact to arc heavily for about 20 minutes was it possible to obtain fairly reproducible results. Table IV shows a summary of results obtained from one of several sets of experiments performed.

Before stabilization of the transient, it was generally observed that the glow period was first short then gradually increased until it reached a limiting value which it did not exceed. These limiting values are given in column 5 as fractions of the half period $\pi(LC)^{1/2}$. They range from zero, actually glow was not detected with a time resolution of 1 per cent of the

TABLE IV — GLOW-ARC TRANSITION DATA FOR PD CONTACTS IN ATMOSPHERIC AIR-CATHODE DIAMETER 0.1 CM.

(1) V_0 volts	(2) C $10^{-12}f$	(3) L $10^{-3}h$	(4) $Z = (L/C)^{1/2}$ ohms	(5) $t_g/\pi(LC)^{1/2}$	(6) $(V_0 - V_g)/L$ 10^4 amp./sec.	(7) (I_g) max. amp.	(8)‡ (i_g) max. amp./cm.^{2}	(9) $(i_g)/i_g$ max.
600	18,000	5	52	0*	6.0	<.018	<2.3	<0.5
500	—	—	—	0	4.0	<.012	<1.6	<0.4
450	—	—	—	0	3.0	<.009	<1.2	<0.3
400	—	—	—	1.0†	2.0	>.19	>23	>4.8
350	—	—	—	1.0	1.0	>.10	>13	>2.6
320	—	—	—	1.0	0.4	>.04	>5	>1.0
600	18,000	8	660	0	3.8	<.015	<2	<0.4
500	—	—	—	0.22	2.5	.19	24	4.8
450	—	—	—	0.44	1.9	.23	29	5.8
400	—	—	—	1.0	1.2	>.15	>19	>3.8
350	—	—	—	1.0	0.6	>.076	>10	>2.0
600	18,000	15	906	0.25	2.0	.23	29	5.8
550	—	—	—	0.30	1.7	.23	29	5.8
500	—	—	—	0.35	1.3	.20	26	5.2
450	—	—	—	1.0	1.0	>.17	>22	>4.4
400	—	—	—	1.0	0.7	>.11	>14	>2.8
600	18,000	20	1050	0.40	1.5	.28	36	7.2
550	—	—	—	0.40	1.2	.23	29	5.8
500	—	—	—	1.0	1.0	>.19	>24	>4.8
450	—	—	—	1.0	0.8	>.14	>18	>3.8

* No glow was detected with a time resolution of 1 per cent of a half period $\pi(LC)^{1/2}$.

† Uninterrupted glow occupied the entire half period.

‡ Obtained by dividing $(I_g)_{\max}$ by the total cathode area.

transient time, to a full transient time. By calculation, the corresponding limiting currents and limiting current densities were obtained, columns 7 and 8 respectively. The ratios of the limiting current densities to the normal glow current density are also given in column 9. They show that at the interruption of the glow discharge the current density was 5 to 7 times the normal glow current density. This indicates a transition from normal glow to abnormal glow before the final transition into an arc. One may, therefore, conclude that if glow discharge is obtained it starts as normal glow which may occupy only a small fraction of the cathode area. By increasing the current the cathode glow area expands at constant current density until it covers the entire cathode area. Further current increase leads to a transition into abnormal glow with higher current densities. Transition of the abnormal glow into an arc occurs when the current density reaches a limiting value. This limiting current density is extremely sensitive to surface contamination and generally

increases with surface cleaning.* For clean Pd contacts in atmospheric air an average limiting current density of 30 amps/cm^2, or about 6 times the normal glow current density, was obtained. This sudden transition from the low current density glow to the very high current density arc represents a high rate of change in the emission process. With contaminated contacts, this is probably due to the presence of low work function high emission spots on the cathode. These spots may be eliminated by proper cleaning thus allowing glow discharge to be maintained at higher current densities. The observed glow-arc transitions for clean contacts, consistently occurring at about 30 amps/cm^2 for Pd, *may still be attributed to the formation of a surface film on the cathode through a cathode-atmosphere reaction.*†

Measurements have also indicated that under certain conditions, glow discharge cannot be obtained even at currents much below the limiting currents discussed above. It appears that there is a limiting rate of rise of current with time above which glow discharge cannot be maintained. In Table IV, column 6, the initial rates of current rise are given. In all cases where the rate of current rise was greater than about 3×10^4 amps/sec, lines 1, 2, 3 and 7, no glow was obtained. The experiment was repeated with two other cathode diameters of 0.2 and 0.05 cm. The limiting rates of rise obtained were approximately the same as given above, indicating that the limiting rate of current rise is independent of the cathode area. This seems reasonable since at the beginning of the transient the currents are very small and the emission area is only a very small fraction of the cathode area. No detailed explanation, however, can be furnished at this time as to why such a limit of the rate of current rise does exist. It is obvious, nevertheless, that while the rate of current rise can be increased without limit by manipulating the circuit parameters, the conduction mechanism in the contact gap, will, in general, have its own limitations as determined by the emission processes involved.

ACKNOWLEDGMENT

I am indebted to Miss R. E. Cox for assistance with many of the experiments and calculations reported here.

* With a contaminated cathode surface a transition into an arc may occur during the *normal* glow period well before the current is high enough to allow normal glow to cover the entire cathode surface. This is particularly true with larger cathode areas which are usually hard to clean satisfactorily by the above procedure.

† A recent unpublished study by F. E. Haworth has shown that in the absence of the usual surface contaminants, glow discharge is capable of activating palladium and silver contacts through the formation of surface films. These surface reactions appear to be strongly dependent on the atmosphere.

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